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EFFECT OF BITUMEN EMULSION ON MECHANICAL PERFORMANCE OF COLD ASPHALT MIXTURES

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Abstract. *Implementation of innovative material and evaluation concepts in pavement construction industry is important to reduce the negative environmental impacts. The objective of this paper is to review the recent scientific developments in characterising the effect of bitumen emulsion properties on the performance of cold asphalt mixtures. The experimental approach was based on the indirect tensile testing of the standardised bitumen emulsion mortar specimens. The major finding is that there is a continuous change in mechanical properties and the mode of fracture on the long-term basis. However, the ratios of the considered fracture performance-related parameters indicated that the change in the mode of fracture from ductile to brittle is not that direct, and the reason for this could be in the relation between the development of the adhesion and the residual binder viscosity. As a step towards fundamental understanding of the contribution of adhesion, further research should be focused on the interaction between cement hydration, binder droplets, and emulsifier.*

Key words: *bitumen emulsion, asphalt mixtures, indirect tensile testing, mechanical performance, fracture*

1. INTRODUCTION

The environmental impact becomes a very important issue in pavement construction industry, too. Therefore, it is necessary to put an accent on the research, development, and implementation of various innovative material and evaluation concepts with a considerable competitiveness to the conventional hot asphalt technologies. In this regard, there is an even more increasing application of composite materials which include bitumen emulsion and cement which are, with slight modifications, used for both asphalt pavements and high speed railways. For the cold asphalt pavement layers, the mixtures with the prevailing role of the bituminous binder are preferred, while in the high speed railways, preferred are the mixtures with the predominant role of cement [1–7].

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Common for both bitumen and cement is that their mechanical properties strongly depend on the curing time and conditions [8–11], although the mechanisms of their build-up are quite different — breaking and coalescence of the bitumen emulsion and hydration of cement. In addition, the bitumen has a typical colloid structure [12], by which mechanical transitions from a Newtonian fluid to the viscoelastic state, and finally to the elastic glassy solid, is driven by a reduction in temperature [13]. Therefore, the microstructure of the matrix created by the interaction of the bitumen and the cement hydration products also determines at which curing stages and the test conditions effect of which of the binders plays a more important role.

The mechanisms of the mechanical properties development are substantially different for the bitumen emulsion and the cement bound mixtures. The cement is a hydraulic binder and its hydration products are brittle with higher compressive strength and stiffness, whereas the bitumen is a viscoelastic binder with much lower stiffness at room temperature. The incremental addition of the bitumen emulsion results in a change of the co-binder's microstructure, and thus, reduces the stiffness and increases the temperature sensitivity of the composite [14]. For this reason, at low bitumen emulsion contents, the phase of the cement hydrates acts as the bulk fibrous matrix (skeleton) with bitumen dispersed in it [15], whereas at high emulsion contents, the bitumen phase becomes dominant and the cement hydrates play the role of the dispersed phase [16–17]. Higher bitumen content can lead to wrapping the cement particles by the bitumen film, and thus, suppress the formation of hydration products by making the water from the emulsion unavailable for the reaction [18]. Consequentially, the composite's mechanical performance, with a time development as a typical feature [19–25], is a combination of both binders' behaviour [26].

While the impact of the cementous binder is directly influenced by the cement type [20], the bituminous phase does not solely influence the behaviour of the bitumen emulsion, but is dramatically affected by the emulsifier, too. The emulsifier enables the production of the emulsion and significantly determines its stability by drawing the water between the bitumen droplets, which is, on the other side, consumed by cement hydration. In this way, the emulsifier has a retarding effect on cement hydration, which increases with the mass ratio of emulsifier to cement and differs for different emulsifier types [27]. Moreover, it is not eliminated after the emulsion breaking is accomplished, and remains in the binder in some form. Therefore, the emulsifier can be considered as an additional link in the relation between cement and bitumen.

The objective of this paper is to review the recent scientific developments in characterising the influence of bitumen emulsion properties on the performance of cold asphalt mixtures and the effect of different emulsion properties on that performance.

2. EXPERIMENTAL METHOD

The characterising method was based on the bitumen emulsion mortar (BEM) mixture with a standardised composition which minimised the potentially variable influence of geometrical, chemical, and mechanical properties of the mineral aggregate. In this regard, the mixture was composed of the bitumen emulsion, cement, limestone filler, and natural quartz sand of the upper sieve size of 2 mm. The aggregate mixture was selected to have the particle size distribution close to the CEN Standard Sand. It contained 7.5 % of limestone filler and 92.5 % of natural quartz sand with the upper sieve size of 2 mm by mass. The particle size distribution of the mineral aggregate is shown in Fig. 1. The contents of the bitumen emulsion were 10, 11, and 12 %. In the mixture, cement CEM I

42.5 N in the amount of 1.5 % by mass was also used. Properties of the bitumen emulsions are provided in **Table 1**.

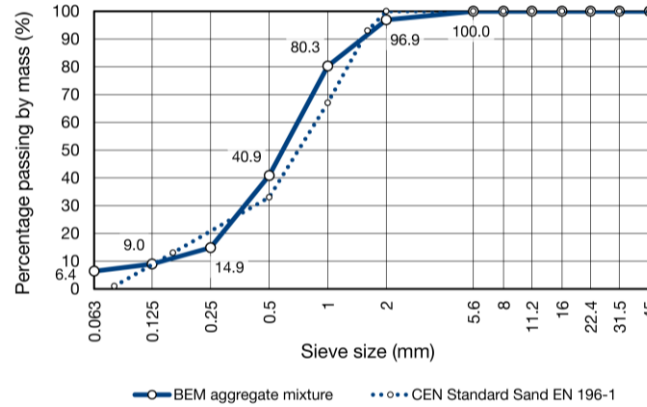


Fig. 1 Particle size distribution of the mineral aggregate mixture

Table 1 Properties of the bitumen emulsions [17]

Designation of the bitumen emulsion	BE1	BE2	BE3
Paving grade bitumen the emulsion was produced from	50/70	70/100	160/220
Perceptible properties (EN 1425)	Brown, liquid, homogeneous		
Breaking behaviour, $BV_{SikaSol}$ (EN 13075-1)	121	127	129
Mixing stability with cement, S_c (g) (EN 12848)	0.9	0.9	0.9
Binder content, 100 % - w (%) (EN 1428)	60.0	60.0	60.0
Residue on sieve 0.5 mm, $R_{0.500}$ (%) (EN 1429)	0.2	0.2	0.1

The cylindrical specimen of 150 mm in diameter and (125 ± 5) mm in height were compacted from approximately 4500 g of the mixture by applying the static compaction principle. In this compaction method, the compaction was made possible from both sides by enabling the free movement of both loading plates. The compaction equipment setup is illustrated in Fig. 2. The compaction began with the constant rate of 20 mm/min until the force of 49 kN was reached. Thereafter, the force was fixed at 49 kN and the mixture was compacted by the constant static load for 3 min from both sides [17].

The compacted specimens were left in the moulds for the first (24 ± 2) h in a horizontal position. Thereafter, the specimens were extracted from the moulds and stored upright on a metal plate for the next two days. The first three days after the compaction, the specimens were cured at (20 ± 2) °C and the relative air humidity of 95 %. However, omitting this step is going to be considered in the future research stages. Three days after the compaction, started, so called, dry curing at the same temperature and the relative air humidity of (65 ± 5) %. Just before the testing, the specimens were conditioned for 8 h at 5 °C in an environmental chamber.

The mechanical properties of the specimens were determined by indirect tensile testing performed 28 days after compaction at 5 °C. The load was applied at the constant rate of (50 ± 2) mm/min over a loading strip of (19.1 ± 0.2) mm in width. The lateral

displacements were measured by two extensometers. An illustration of the indirect tensile testing setup with relevant stresses and areas in which the failure occurs is shown in Fig. 3.

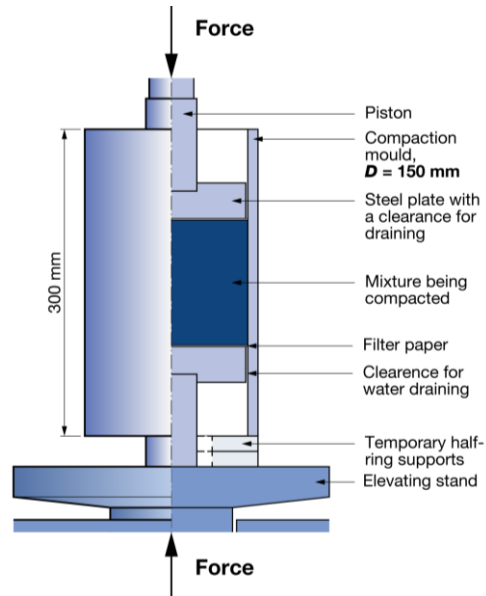


Fig. 2 Specimen compaction setup (adjusted for the specimen diameter of 100 mm)

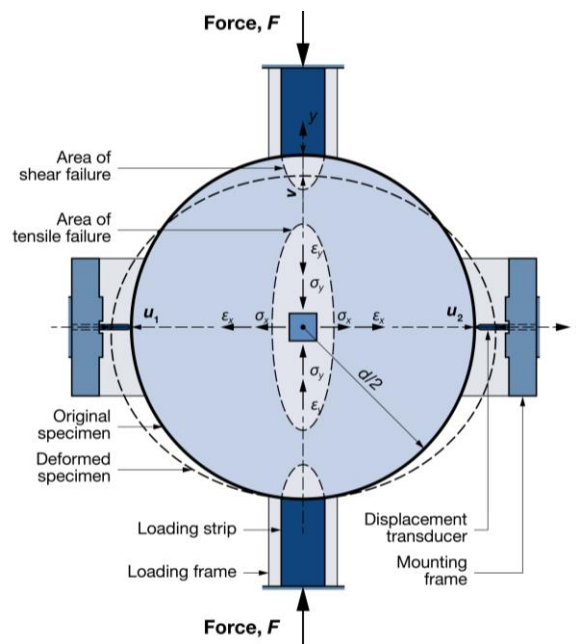


Fig. 3 Indirect tensile testing setup [27]

According to the data obtained from the force-displacement dependencies, the indirect tensile strength, ITS , the failure strain, ε_{IT} , and the tangent stiffness modulus corresponding to 45 % of the failure load, E_{IT} , were calculated by using the following equations:

$$ITS = \frac{2F}{\pi d h} \quad (1)$$

$$\varepsilon_{IT} = \frac{2u}{d} \frac{(1+3\nu)}{(4+\pi\nu-\pi)} \quad (2)$$

$$E_{IT} = \frac{0.45F(4+\pi\nu-\nu)}{\pi h u_{45\%}} \quad (3)$$

and the specific fracture work, W^* , and the deformation energy, U^* , were calculated by using the following equations:

$$W^*(v) = \frac{4}{\pi d^2 h} \int_v F(v) dv = \frac{4}{\pi d^2 h} I_v \quad (4)$$

$$U^*(u) = \frac{4}{\pi d^2 h} \cdot \frac{1+3\nu}{4+\pi\nu-\pi} \int_u F(u) du = \frac{4}{\pi d^2 h} \cdot \frac{1+3\nu}{4+\pi\nu-\pi} \cdot I_u \quad (5)$$

where F is the maximum vertical load achieved during the test and it corresponds to the point of failure, d is the specimen diameter, h is the specimen height, u is the total lateral displacement, i.e. $u_1 + u_2$, ν is Poisson's ratio (assumed to be 0.3), $u_{45\%}$ is the total lateral displacement at 45 % of the maximum load, v is the measured vertical displacement of the loading strips, and $F(v)$ and $F(u)$ are the dependencies of the load from the vertical and the horizontal (lateral) displacement, respectively. To distinguish, whether the integration was done to the failure point or for the entire diagram, the W^* and U^* values calculated for the total failure, i.e. the fracture were denoted with W^*_t and U^*_t , respectively.

3. RESULTS

3.1. General mechanical properties

The results of the indirect tensile strength, the failure strain, and the tangent stiffness modulus corresponding to 45 % of the failure load, were determined for 7, 28, and 84 days after curing are shown in Fig. 4, Fig. 5, and Fig. 6.

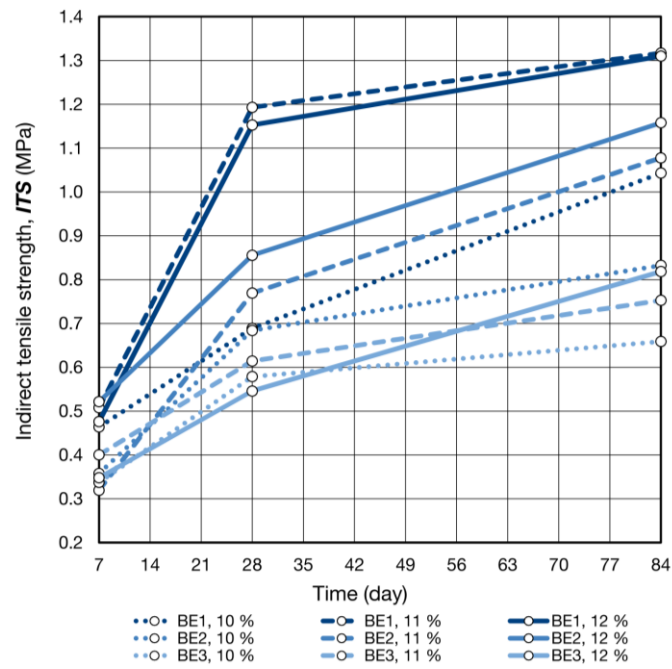


Fig. 4 Dependency of the indirect tensile strength over time [17]

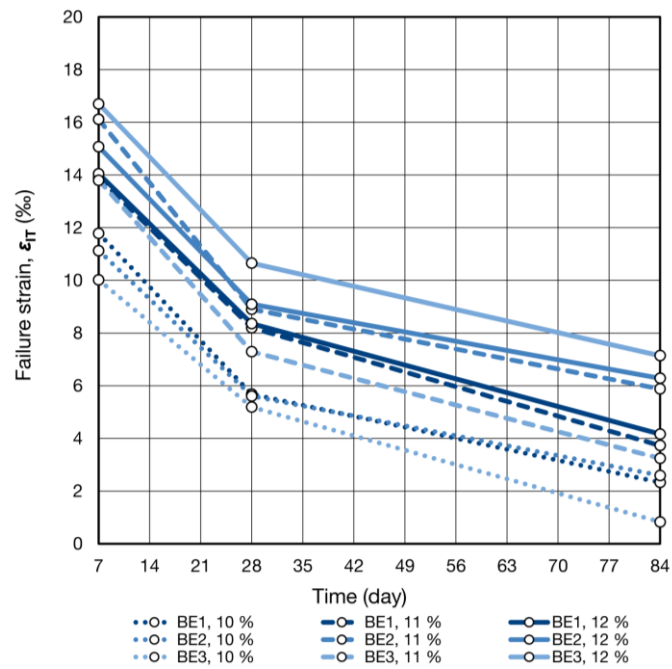


Fig. 5 Dependency of the failure strain over time [17]

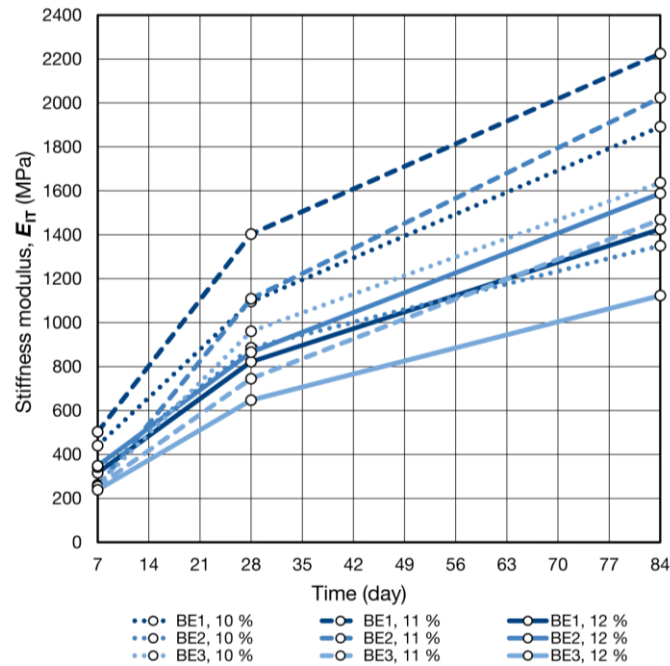


Fig. 6 Dependency of the stiffness modulus over time [17]

The indirect tensile strengths experienced a significant increase from 7 to 28 days of curing of 0.43 MPa in average. This means that the strengths after 28 days was approximately double the strengths after 7 days of curing. The increase in the strengths of 0.21 MPa in average from 28 to 84 days was also considerable. It is noticeable that as higher the increase of the indirect tensile strength between 7 and 28 days is, the lower it is between 28 and 84 days of curing.

The failure strains showed a very noticeable tendency to decrease over time. Furthermore, a clear propensity of the failure to become more brittle over time could also be observed. Moreover, it is noticeable that the range of the failure strain values remained approximately 6.0 % over the entire considered time period, and the differences between the values for the single mixtures were mostly unchanged.

The stiffness modulus was the mechanical parameter with the most considerable increase from 7 to 84 days. The relationship between the single values was mostly unchanged after 7, 28, and 84 days of curing, which facilitates estimating the stiffness modulus after 28 based on 7 day-values, and similarly, estimating the stiffness modulus after 84 based on the 28 day-values [17].

3.2. Fracture energy-related performance

The fracture work related properties were calculated for 7, 28, and 84 days of curing. The time dependencies of the W^* to W^*_t and U^* to U^*_t ratios of the considered BEM mixtures are shown in Fig. 7 and Fig. 8, respectively.

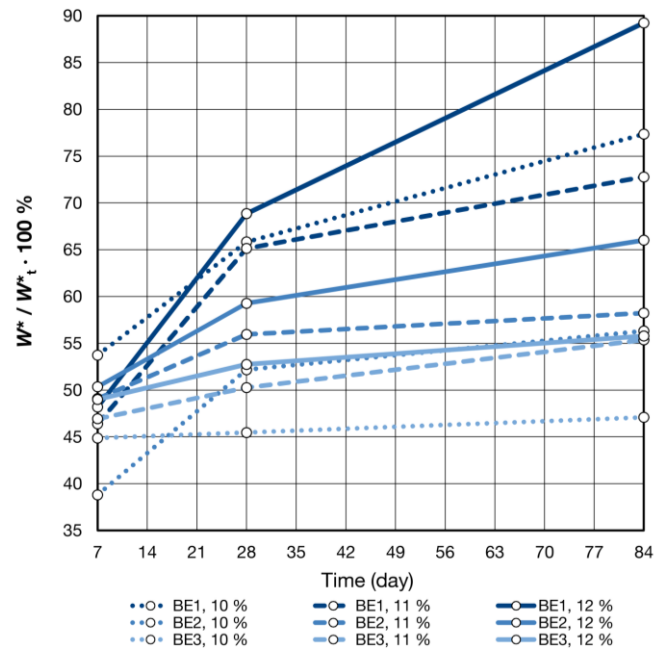


Fig. 7 Dependency of the specific to total specific fracture work ratio over time [26]

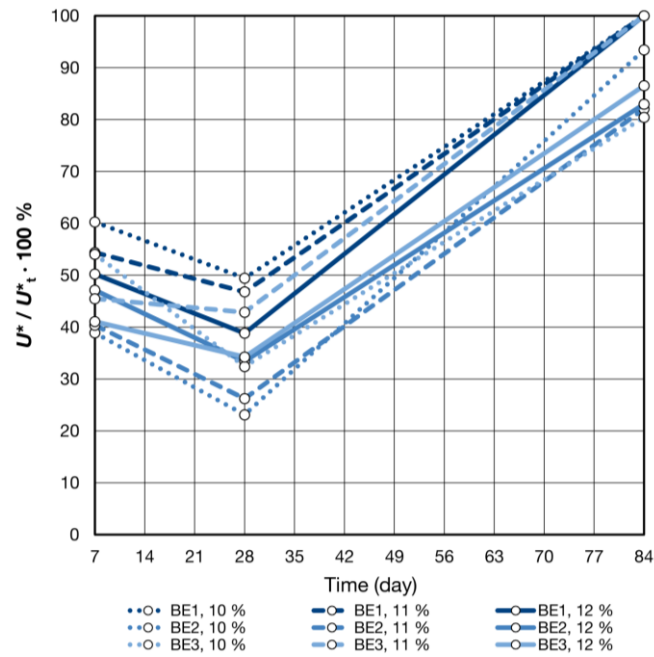


Fig. 8 Dependency of the deformation energy to total deformation energy ratio over time [26]

The results of the W^* to W_t^* ratios indicate that the specimens with 12 % of BE1 had the most brittle, while the specimens with 10 % of BE3 had the most ductile fracture behaviour. The values after 7 days of curing had the lowest dispersion and were mostly concentrated between 45 and 50 %. The average increase from 7 to 28, and from 28 to 84 days of curing was 9.8 % and 6.9 % in average, respectively. However, the rate of that increase considerably differed depending on the mixture type, and the values with 12 % of BE1 reached approximately 89 % which was almost a pure brittle fracture, while the mixtures with BE3 experienced only a minor change in W^* to W_t^* ratio [26]. A photograph of a broken edge of the specimen made by an optical microscope is shown in Fig. 9.

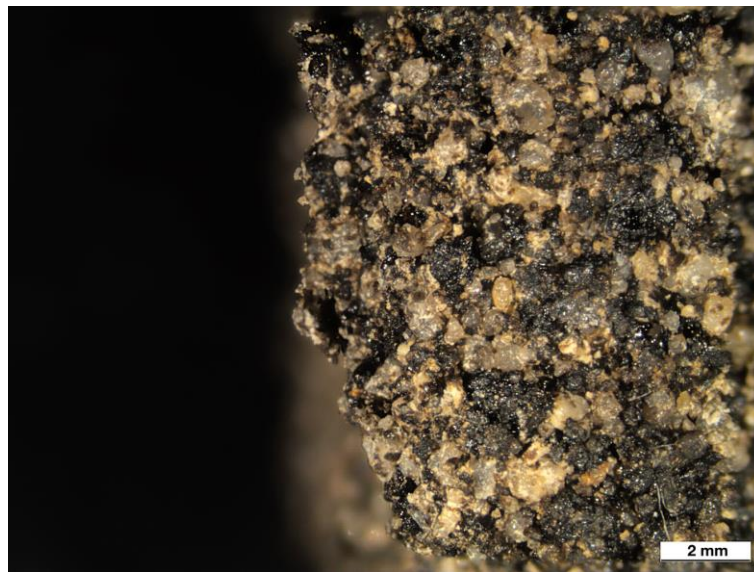


Fig. 9 Photograph of a broken edge of the specimen after testing

4. CONCLUSIONS

Very indicative is that there is still a significant change in general mechanical parameters far after 28 days of curing. The results confirmed that the mixtures with higher bitumen emulsion contents are more sensitive to the bitumen viscosity. Additionally, harder binder resulted in higher indirect tensile strengths, reason for which could be the higher bulk densities achieved by the compaction [27].

The dependencies of the deformation energy ratio indicated that the specimens become more ductile from 7 to 28 days of curing and more brittle up to 84 days of curing. However, on the long-term basis, the fracture of all the mixtures was clearly brittle. Reason for such behaviour could be processes in the contact regions between the sand particles. Thus, the adhesion between the binder and the sand develops faster, which causes the cohesive failure and the ductile fracture at the beginning of the curing period. Thereafter, the coalescence of the emulsion is completed and the original stiffness of the bitumen plays a dominant role. At this point, the adhesive failure occurs and the fracture is brittle.

The future research should consider the process of the cement hydration in the presence of the bitumen droplets and the role of the emulsifier. This knowledge would provide a base for evaluation of the behaviour of the water in the cold asphalt mixtures, and thus, facilitate the research on the effect of adhesion between the binder and the aggregate on the resulting mixture performance.

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UTICAJ BITUMENSKE EMULZIJE NA MEHANIČKO PONAŠANJE HLADNIH ASFALJNIH MEŠAVINA

Implementacija inovativnih koncepata materijala i njihovog vrednovanja u građenju kolovoznih konstrukcija je važno za smanjenje negativnog dejstva po životnu sredinu. Predmet ovog rada je pregled aktuelnih kretanja u nauci u pogledu karakterizacije uticaja osobina bitumenske emulzije na ponašanje hladnih asfaltnih mešavina. Eksperimentalni pristup je bio zasnovan na ispitivanju probnih tela od standardizovanog maltera bitumenske emulzije indirektnim zatezanjem. Najznačajniji rezultat je postojanje neprekidne promene mehaničkih osobina i vrste loma na dugoročnoj osnovi. Međutim, odnosi razmatranih parametara u vezi sa ponašanjem u pogledu su pokazali da promena vrste loma, od duktilnog do krto, nije potpuno direktna, a razlog za ovo bi mogao da bude odnos između razvoja adhezije i viskoziteta rezultirajućeg veziva. Kao korak ka fundamentalnom razumevanju doprinosa adhezije, dalje istraživanje bi trebalo da bude usredsređeno na interakciju između hidratacije cementa, kapljica veziva, i emulgatora.

Ključne reči: *bitumenska emulzija, asfaltna mešavina, ispitivanje indirektnim zatezanjem, mehaničko ponašanje, lom*